The Development of EXPLOSION PUFFING

□ FOOD IS PRESERVED in many ways, but one of the oldest and most effective is by drying. Currently, dehydration of fruits and vegetables is normally accomplished by hot-air drying or freeze drying. Dehydration of pieces by hot air is slow, and practical limits on both time to dry and time to rehydrate exert a severe constraint on piece size (Labuza, 1972). The rehydrated product's quality can approximate that of conventionally prepared fresh material, but flavor especially is degraded by the relatively long exposure to high temperatures during hot-air drying (Duckworth, 1966).

Freeze-dried products rehydrate rapidly and are higher in quality than products from hot-air dehydration (Van Arsdel et al., 1973). However, the drying is slower and more expensive. Because of the high processing and capital investment costs, the use of freeze drying has been limited to foods that cannot be satisfactorily dried by other methods.

A third process incorporates explosion puffing into a hot-air dehydration process (Eisenhardt et al., 1962). Explosion puffing was devised to yield a product similar to freeze-dried, with faster rehydration, retention of the texture and flavor characteristics of fresh-cooked food, and lower unit processing costs. This innovative technique produces low-moisture (<4%) fruit or vegetable pieces, and makes feasible the processing of relatively large pieces, e.g., 1.9-cm cubes; normal hot-air drying of pieces this large is prohibitively slow. This article will review the development of the explosion-puffing process.

EXPLOSION PUFFING

Explosion puffing is incorporated into the hot-air dehydration process at moisture contents between 15 and 35% depending upon the commodity. These moisture contents are in the initial stages of the falling-rate period but where drying is still relatively rapid. Partially dried food pieces (e.g., potatoes at 25% moisture, wet basis) are removed from a dryer, explosion puffed, then returned to the dryer to reduce the moisture to a safe storage condition ($a_W < 0.6$). Figure 1 depicts hot-air dehydration curves for white potatoes, with and without the explosion-puffing step.

Because of the porosity obtained during explosion puffing, drying of these food pieces is accelerated, compared to normal hot-air drying; this results in the saving of at least 40% in drying time. The instantaneous change in pressure that occurs when the water is vaporized does not damage the pieces or even rupture cells; this fact is evident from the texture of these rehydrated foods.

In the explosion-puffing process, the partially dried (15-35% moisture) food pieces are fed to a puffing gun, which is subjected to a predetermined pressure. The pressure is developed externally by gas heating and/or internally by superheated steam (Eskew et al., 1963; Sullivan et al., 1965; Heiland et al., 1977). As the pressure is increased, the water within the food pieces is raised above its atmospheric boiling point. The instantaneous release of the chamber pressure causes the superheated water to flash into steam, thereby creating the porous structure (Eskew et al., 1962) shown in Figure 2 and restoring the pieces to approximately their original shape (Sullivan et al., 1981).

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Many fruits and vegetables have been processed using the explosion-puffing step, and the benefits are evident in their excellent texture, color, and flavor (Turkot et al., 1967). These characteristics have been maintained during extended storage when the products are air-packed at 3.3°C (Sullivan et al., 1981).

INITIAL RESEARCH

Early research determined that fruit and vegetable pieces could not be explosion puffed in a natural or raw state because the pieces disintegrated when puffed. At a pressure specific for each commodity, moisture limits were found between which a porous structure was created without disintegration of the food pieces (Eisenhardt et al., 1962; Stoll et al., 1980). Since a strong interaction exists between the moisture content and the pressure used, the material's strength and the rupturing forces must be balanced. Research was directed toward creating and maintaining this porous structure because the porosity made removal or penetration of water easy and rapid.

The original experiments were made in a small cereal-type "puffing gun" (12 cm in diameter × 25.4 cm in length) heated externally by a gas flame. A charge of fruit or vegetable pieces was heated by an external gas-fired burner while the gun rotated at a speed which imparted a tumbling action to the food pieces. The puffing gun was in a horizontal position during rotation. The chamber pressure developed from steam evolved from the fruit or vegetable being tested. The time required to develop the explosion-puffing pressure from this type of puffing gun ranged from 7 to 15 min, after which the rotation was stopped and the puffing gun was placed in the discharge position. The lid was then released by manually striking an eccentric cam lock. The product exploded from the puffing gun, with a loud bang, into a wire-mesh collecting cage.

This puffing gun had the capacity for only small quantities of fruit or vegetables (about 1 kg). Thus, it gave the opportunity to make many experiments to test the feasibility of explosion puffing. The studies included (1) determinations of the relationship of puffing pressure, moisture content, and degree of rehydration and (2) comparisons of drying times with and without the explosion-puffing step.

A definite pressure-moisture relationship was found. This relationship was somewhat different for each food tested. For example, potatoes require a pressure of about 450 kPa at 25% moisture, while apples require only 100 kPa at 20% moisture. Increasing the pressure at these moisture contents led to disintegration, while lowering it reduced puffing. A deviation in moisture content at these pressures resulted in disintegration or charred products.

The best explosion-puffing conditions in these early experiments were determined primarily by two methods. First, drying curves of air-dried foods were compared with drying curves of the explosion-puffed and dried products. Improved porosity gave greater differences in drying time to a specified final moisture content. Second, rehydration of the air-dried samples and the explosion-puffed and dried samples was evaluated for time of rehydration and water pickup.

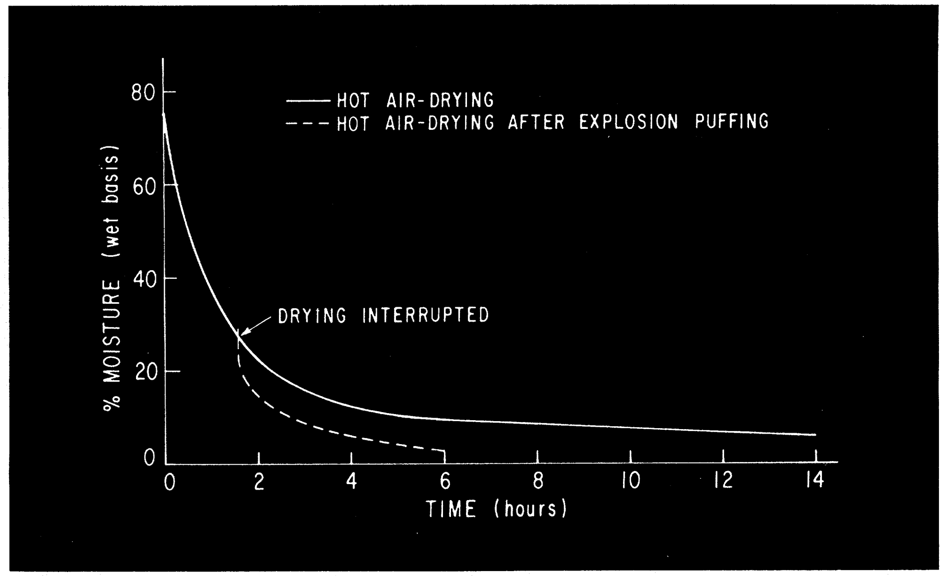

Fig. 1—**HOT-AIR DRYING CURVES** *for potato cubes with and without an explosion-puffing step*

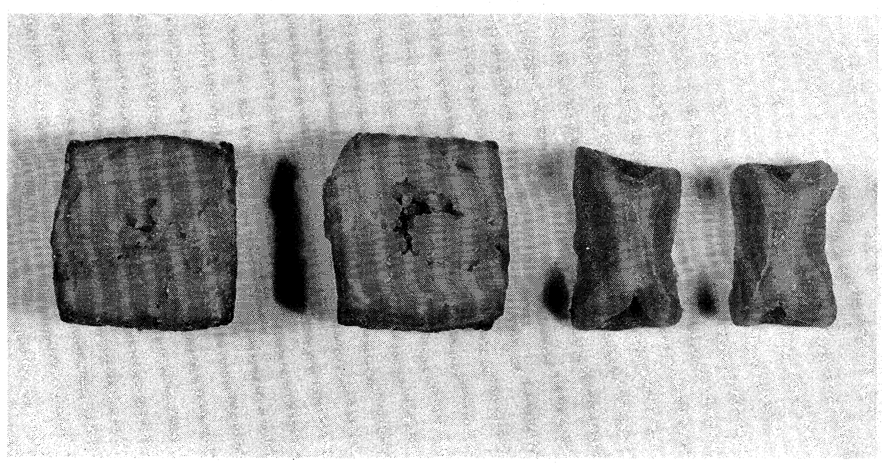

Fig. 2—**CROSS-SECTIONS** *of explosion-puffed potato cube (two halves at left) and conventionally air-dried potato cube (two halves at right)*

BATCH SCALE-UP

The process was scaled-up by installing a large commercial cereal-puffing gun (25 cm in diameter × 75 cm in length). The scale-up was necessary to obtain reasonable commercial-type feed rates for cost estimations. However, like the smaller one, this puffing gun had drawbacks. The primary ones were that both puffing guns: (1) were made of cast iron with rough interior surfaces, which caused some food pieces to stick to the surface and scorch instead of tumbling freely; (2) had to be opened and closed manually; and (3) had to be closed against a sealing ring made of lead (which did not contact the food).

The scale-up studies included the relationship of charge size, puffing pressure, and moisture content, as well as the parameters studied earlier. Bulk density determined the loading capacity. Partially dried 1-cm cubes of potato and carrot were tested in batch sizes ranging from 0.5 to 11.4 kg. A charge size occupying 70% of the puffing-gun volume (9 kg in the case of the 1-cm potato and carrot cubes) was found to be close to optimum.

A second large puffing gun (same dimensions) was constructed to eliminate some of the earlier problems. The interior was sand-blasted and nickel-plated, a shock absorber was installed to take the recoil from the lid, and a heat-tolerant rubber gasket was used for sealing. Rubber could be used instead of lead because the explosion puffing of fruits and vegetables required much lower operating pressures (500 kPa or lower) than explosion puffing of cereals.

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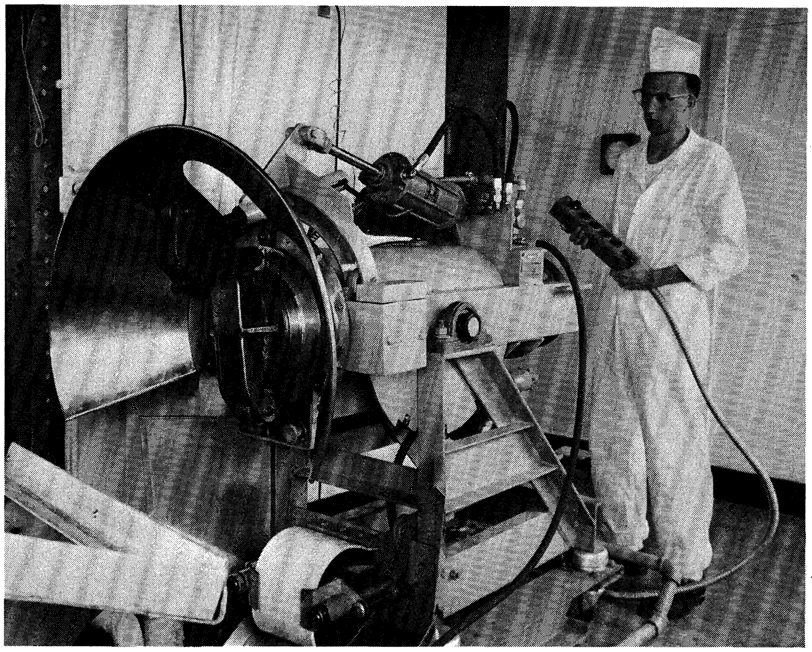


Fig. 3 (above)—**BATCH EXPLOSION-PUFFING GUN**

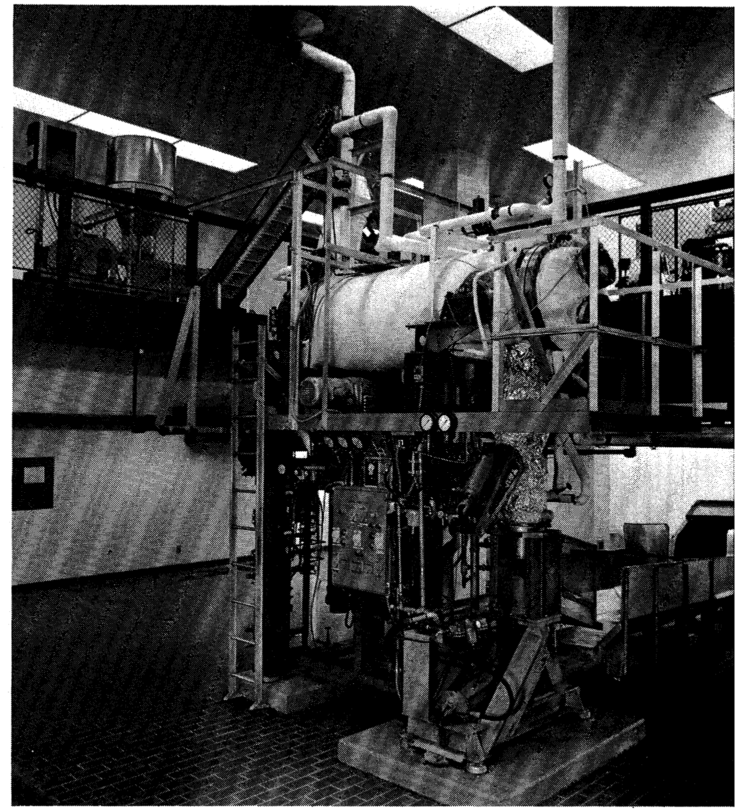
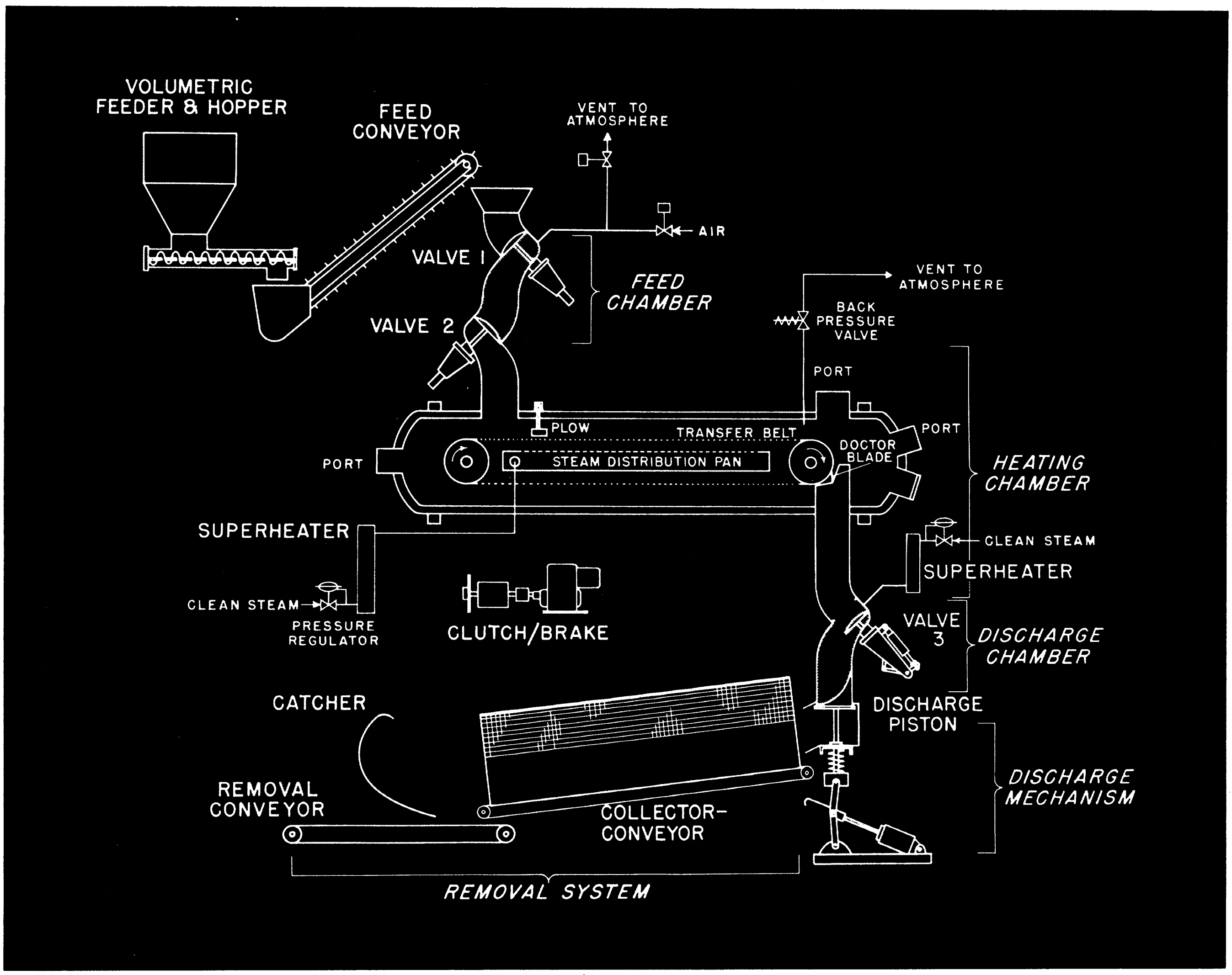


Fig. 4 (right)—**CONTINUOUS EXPLOSION-PUFFING SYSTEM**

Fig. 5 (below)—**SCHEMATIC** *of the Continuous Explosion-Puffing System*



However, this puffing gun, like the other two, also had faults—manual closing and long operational cycles of 7-15 min. This dictated the design and fabrication of a third batch puffing gun.

This final experimental batch puffing gun (Fig. 3) was designed exclusively for explosion-puffing of fruits and vegetables, not of cereals. Because of lower pressure requirements, the wall thickness could be reduced. Also, a self-cleaning nozzle and a pneumatically locking and opening lid were added for ease of operation, and longitudinal fins were added for better heat transfer. This puffing gun was used for all subsequent batch work (Heiland and Eskew, 1965). It was constructed to be heated internally by superheated steam and externally by gas burners. The heating cycle was reduced to 1-2 min by introducing superheated steam, which supplied the pressure and heat for puffing (Sullivan et al., 1965). Temperature of the superheated steam is kept 15°C above the condensation temperature of the selected explosion-puffing pressure; higher superheated-steam temperatures cause discoloration of the products. Many deficiencies of the commercial batch puffing guns were eliminated; as a result, product quality (color and flavor) improved. Although this puffing gun was designed for pilot-plant research, it can also be utilized commercially (Turkot et al., 1965; 1967).

Table 1—**COLOR DIFFERENCES** *between fresh-cooked and explosion-puffed carrot and celery*

Sample	Gardner color difference values[a]		
	Rd	a	b
Carrots			
Fresh-cooked	19.6	22.0	33.0
Rehydrated explosion-puffed	21.29	24.5	33.85
Celery			
Fresh-cooked	18.7	−5.1	23.3
Rehydrated explosion-puffed	15.6	−5.5	23.1

[a]Average of three readings

CONTINUOUS OPERATION

Batch scale was convenient and practical for research but was labor intensive. To reduce processing costs and improve scale-up and control of the explosion-puffing process, a Continuous Explosion-Puffing System (CEPS) was designed and built (Heiland et al., 1977). This system, shown in Figures 4 and 5, separated the two major functions of the process: heating and explosion puffing. The heating is accomplished in the "main" or heating chamber by dispersing superheated steam through the perforated stainless-steel transfer belt. Explosion puffing occurs when valve 3 is closed and the discharge piston instantly released, reducing the pressure in the discharge chamber from that in the heating chamber to atmospheric. The system is responsive, with pressure and/or temperature changes reflected rapidly in product color and quality of puff. The use of CEPS resulted in better process control, improved product quality, and reduced labor costs. Once the system —feed rate, feed (raw material) moisture content, internal pressure, internal temperature, and discharge rate—has reached steady state, it operates with minimal care and only occasional operational adjustments.

The capacity of the CEPS was found to be 190 kg/hr for apple half-segments (15% moisture, wet basis) (Sullivan et al., 1980); and the system would easily process 454 kg/hr of 1-cm cubes of potato (25% moisture, wet basis) (Sullivan et al., 1977; 1983). Carrots (Sullivan et al., 1981) and blueberries (Sullivan et al., 1982) have also been processed successfully. All fruits and vegetables that were processed successfully during batch research—beets, celery, onion, peppers, rutabagas, sweet potatoes, turnips, and pears—can be processed in the continuous system.

OFFERS BENEFITS

The high quality of the dehydrated products (texture, flavor, and color) is a characteristic of the explosion-puffing process. Flavor and color changes occur because of oxidation and/or the formation of nonenzymatic browning compounds. Change in color or in absorbance at 420 nm caused by nonenzymatic browning is minimal when comparing fresh-cooked foods to rehydrated explosion-puffed counterparts (Table 1). For example, the absorbance of fresh-cooked carrots was 27, whereas that of rehydrated explosion-puffed carrots was 33.4. Excessive nonenzymatic browning occurred during the processing of white potatoes, but only when batch puffing guns were used. This problem was solved by incorporating an inert gas into the superheated-steam stream (Cording and Sullivan, 1973). Qualified organoleptic taste panels have repeatedly rated rehydrated explosion-puffed food texture excellent. The quality is retained during storage (Sullivan et al., 1981; Konstance et al., 1978).

Rapid drying and reconstitution are equally important traits, and the process becomes more advantageous as the piece size increases, because of porosity. Porosity obtained during the explosion-puffing step is not lost during further drying; thus, case hardening is not a problem. An experiment was made with 1.9-cm cubes of potato that were air dried with and without explosion puffing. Drying conditions—air velocity, temperature, tray loading, piece size, and variety—were the same in both cases. The cubes dried with the explosion-puffing step took 7 hr to reach 7% moisture, whereas the air-dried cubes took 30 hr and only reached 15% moisture. Rehydration of the explosion-puffed product was much faster—10 min, compared to more than 90 min for the air-dried product.

The explosion-puffing step can have a considerable impact in food dehydration by reducing total drying time. Shorter processing times mean smaller equipment and less capital spent, and the difference can be used to amortize CEPS. Reconstitution of explosion-puffed foods is quick and about 5-6 times faster than that of hot-air-dehydrated foods. At present, explosion-puffed and hot-air-dried carrots sell at the same price.

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Explosion-puffed food's nearest quality competitor, freeze-dried food, suffers from high operational costs, difficulty in converting from batch to continuous operation, and a paucity of recent equipment development.

The explosion-puffing principle has potential for application to other foods not studied, and to nonfoods whose thermal history and final moisture requirements are similar to those of foods.

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